MAGNETIC RESONANCE IMAGING WITH REAL-TIME MAGNETIC FIELD MAPPING

DESCRIPTION

The following relates to the magnetic resonance arts. It finds particular application in magnetic resonance imaging scanners employing substantial amounts of steel to shim or shape the main B_o magnetic field, and will be described with particular reference thereto. However, it also finds application in other magnetic resonance imaging scanners and in magnetic resonance spectroscopy and imaging techniques that benefit from maintaining a substantially uniform main B_o magnetic field or that benefit from information about non-uniformities of the main B_o magnetic field.

Magnetic resonance imaging scanners are increasing utilizing steel or other ferromagnetic material within the main B_o magnetic field. Shims of steel or other ferromagnetic material are commonly used to correct magnets for manufacturing flaws. Rings, bars, or other configurations of steel or other ferromagnetic material are also sometimes incorporated into magnet designs. For example, in short bore magnetic resonance imaging scanners steel rings or other steel structures can be used to stretch the uniform magnetic field to compensate for the shorter bore, and to compensate for main B_o magnetic field non-uniformities introduced by the shortening of the bore.

While addition of steel or other ferromagnetic material in the main B_o magnetic field can be beneficial to initial field homogeneity, a problem can arise in that cycling of magnetic field gradients during extended imaging sessions can induce eddy currents that heat the steel. Such heating affects the magnetic characteristics of the steel and can shift the main B_o magnetic field and/or introduce spatial non-uniformities in the main field over the course of an imaging session.

There are other situations in which the main B_o magnetic field can drift or otherwise change over the course of an imaging session. If, for example, the main B_o magnetic field is not fully stabilized, such as if the overall field intensity or the field-of-view is adjusted, long time-constant transients can manifest as main field drift or distortion. Imperfections in the main magnet power controller electronics can also introduce drift.

To account for non-uniformities of the main B_o magnetic field, the main field can be mapped using various techniques, such as the FASTERMAP technique

described in Shen et al., *Magn. Reson. Med.* vol. 38, pages 834-839 (1997). These mapping techniques typically involve several seconds of data acquisition and are performed prior to performing an imaging session. They do not account for changes in the main B_o field due to heating of steel, drift in the main magnet current, or the like, which occur over the course of the imaging session or during an individual scan.

The present invention contemplates an improved apparatus and method that overcomes the aforementioned limitations and others.

According to one aspect, a magnetic resonance method is provided. Magnetic resonance imaging is performed in a main magnetic field. Spatial data corresponding to the main magnetic field is measured. At least one main magnetic field nonuniformity parameter is determined from the spatial data corresponding to the main magnetic field. The measuring and determining are performed concurrently with the performing of magnetic resonance imaging.

According to another aspect, a magnetic resonance imaging apparatus is disclosed. A means is provided for performing magnetic resonance imaging in a main magnetic field. A means is provided for measuring spatial data corresponding to the main magnetic field. A means is provided for determining at least one main magnetic field nonuniformity parameter from the spatial data corresponding to the main magnetic field.

According to yet another aspect, a magnetic resonance imaging apparatus is disclosed. A magnetic resonance imaging scanner performs magnetic resonance imaging. The scanner includes a main magnet generating a main magnetic field, magnetic field gradient coils, and at least one radio frequency antenna. At least one magnetic field sensor measures spatial data corresponding to the main magnetic field. A processor is programmed to determine a main magnetic field nonuniformity parameter.

One advantage resides in providing main B_o magnetic field mapping over the course of an imaging session.

Another advantage resides in compensating for changes in the main B_o magnetic field occurring over the course of an imaging acquisition or session.

Yet another advantage resides in providing more accurate imaging by maintaining a substantially uniform main B_o magnetic field over the course of an imaging session.

Still yet another advantage resides in providing information on main B_o magnetic field non-uniformities concurrently with magnetic resonance imaging. The provided information can be used to adjust the main B_o magnetic field to compensate for the field non-uniformities. Additionally or alternatively, the provided information can be used post-data acquisition to correct the acquired magnetic resonance imaging data for artifacts caused by the field non-uniformities.

Numerous additional advantages and benefits will become apparent to those of ordinary skill in the art upon reading the following detailed description of the preferred embodiments.

The invention may take form in various components and arrangements of components, and in various process operations and arrangements of process operations. The drawings are only for the purpose of illustrating preferred embodiments and are not to be construed as limiting the invention.

FIGURE 1 diagrammatically shows a magnetic resonance imaging system implementing rapid main B_o magnetic field mapping operating concurrently with magnetic resonance imaging.

FIGURE 2 diagrammatically shows a magnetic resonance-based magnetic field sensor for measuring the main B_o magnetic field.

FIGURE 3 diagrammatically shows a Hall effect magnetic field sensor for measuring the main B_o magnetic field.

FIGURE 4 shows a magnetic resonance pulse sequence implementing one embodiment of rapid main B_o magnetic field mapping.

FIGURE 5 plots a timing sequence of imaging frames or dynamics with interspersed main B_o magnetic field mapping sequence measurement and calculation timeframes. A timeframe for a typical FASTERMAP magnetic field mapping sequence is also illustrated for comparison.

FIGURE 6 diagrammatically shows details of the shimming processor of FIGURE 1.

With reference to FIGURE 1, a magnetic resonance imaging scanner **10** includes a housing **12** defining a generally cylindrical scanner bore **14** inside of which an associated imaging subject **16** is disposed. Main magnetic field coils **20** are disposed inside the housing **12**, and produce a main B_o magnetic field directed generally along and parallel to a central axis **22** of the scanner bore **14**. The main magnetic field coils **20** are typically superconducting coils disposed inside cryoshrouding **24**, although other main magnet geometries and magnetic sources may also be used.

In one embodiment, an array or structure **26** of steel or another ferromagnetic material is arranged inside the housing **12**. The array or structure **26** interacts with the magnetic field produced by the main magnetic field coils **20** to provide a uniform main B_o magnetic field over a selected field of view. While the array or structure **26** is shown inside the housing **12**, it may also be arranged inside of the scanner bore **14**, for example by mounting the steel or other ferromagnetic material on a dielectric former that slides into the bore **14**. The steel or other ferromagnetic material of the array or structure **26** is preferably laminated, constructed of stacked steel plates, formed as a composite with a non-magnetic material, or otherwise configured to reduce eddy currents. Nonetheless, some eddy currents may form in the array or structure **26**. These eddy currents can heat the steel or other ferromagnetic material and cause changes in the magnetic properties of the array or structure **26** over the course of an imaging session.

The housing **12** also houses or supports magnetic field gradient coils **30** for selectively producing magnetic field gradients parallel to the central axis **22** of the bore **14**, along in-plane directions transverse to the central axis **22**, or along other selected directions. The housing **12** further houses or supports a radio frequency body coil **32** for selectively exciting and/or detecting magnetic resonances. A coil array **34** disposed inside the bore **14** includes a plurality of coils, specifically four coils in the illustrated example coil array **34**, although other numbers of coils can be used. The coil array **34** can be used as a phased array of receivers for parallel imaging, as a sensitivity encoding (SENSE) coil for SENSE imaging, or the like. In one embodiment, the coil array **34** is an array of surface coils disposed close to the imaging subject **16**. The housing **12** typically includes a cosmetic inner liner **36** defining the scanner bore **14**.

The coil array **34** can be used for receiving magnetic resonances that are excited by the whole body coil **32**, or the magnetic resonances can be both excited and

received by the coil array **34**. Moreover, it is also contemplated to excite magnetic resonance with the coil array **34** and detect the magnetic resonance with the whole body coil **32**. It will be appreciated that if one of the coils **32**, **34** is used for both transmitting and receiving, then the other one of the coils **32**, **34** is optionally omitted.

The main magnetic field coils **20** produce a main magnetic field B_0. A magnetic resonance imaging controller **40** operates magnet controllers **42** to selectively energize the magnetic field gradient coils **30**, and operates a radio frequency transmitter **44** coupled to the radio frequency coil **32** as shown, or coupled to the coils array **34**, to selectively energize the radio frequency coil or coil array **32**, **34**. By selectively operating the magnetic field gradient coils **30** and the radio frequency coil **32** or coil array **34** magnetic resonance is generated and spatially encoded in at least a portion of a region of interest of the imaging subject **16**. By applying selected magnetic field gradients via the gradient coils **30**, a selected k-space trajectory is traversed, such as a Cartesian trajectory, a plurality of radial trajectories, or a spiral trajectory. Alternatively, imaging data can be acquired as projections along selected magnetic field gradient directions. During imaging data acquisition, the magnetic resonance imaging controller **40** operates a radio frequency receiver **46** coupled to the coils array **34**, as shown, or coupled to the whole body coil **32**, to acquire magnetic resonance samples that are stored in a magnetic resonance data memory **50**.

The imaging data are reconstructed by a reconstruction processor **52** into an image representation. In the case of k-space sampling data, a Fourier transform-based reconstruction algorithm can be employed. Other reconstruction algorithms, such as a filtered backprojection-based reconstruction, can also be used depending upon the format of the acquired magnetic resonance imaging data. For SENSE imaging data, the reconstruction processor **52** reconstructs folded images from the imaging data acquired by each coil, and then combines the folded images along with coil sensitivity parameters to produce an unfolded reconstructed image.

The reconstructed image generated by the reconstruction processor **52** is stored in an image memory **54**, and can be displayed on a user interface **56**, stored in non-volatile memory, transmitted over a local intranet or the Internet, viewed, stored, manipulated, or so forth. The user interface **56** can also enable a radiologist, technician, or other operator of the magnetic resonance imaging scanner **10** to communicate with the

magnetic resonance imaging controller **40** to select, modify, and execute magnetic resonance imaging sequences.

Optionally, the main B_o magnetic field is actively shimmed during the course of an imaging session by a shimming processor **60**. In one embodiment, the shimming processor **60** computes one or more shim currents based on magnetic field data acquired by the whole body coil **32** or by the coils of the coils array **34** during a pre-scan dedicated shimming magnetic resonance pulse sequence. The shim current or currents computed by the shimming processor **60** are applied to shim coils **61** of the main magnetic field coils **20** by a main B_o magnetic field shims controller **62**.

In another embodiment, the shimming processor **60** computes shimming current or currents based on measurements of the main B_o magnetic field acquired by an array of magnetic field sensors **64**, **66**, **68**, **70** disposed at selected locations in the bore **14** or inside the housing **12** within the main B_o magnetic field. In addition to the four sensors **64**, **66**, **68**, **70** shown in FIGURE 1, other magnetic field sensors may be disposed on the portion of the scanner **10** that is cut away in the view of FIGURE 1. More generally, two or more magnetic field sensors are disposed at different positions within the bore **14** or inside of the housing **12** to provide spatial information about the main B_o magnetic field. The sensors **64**, **66**, **68**, **70** can be Hall effect magnetic field sensors, magnetic resonance-based sensors such as frequency lock coils, independent resonance-based sensors that include their own dedicated resonance material and radio frequency excitation systems, or so forth.

The magnetic field sensors **64**, **66**, **68**, **70** are monitored by a magnetic field sensors readout **72** that acquires the readings, optionally formats or otherwise processes the readings, and communicates the magnetic field measurements to the shimming processor **60**. In one embodiment, the magnetic field sensors **64**, **66**, **68**, **70** and the magnetic field sensors readout **72** collectively define a magnetic field camera that outputs magnetic field non-uniformity measurements in the form of spherical harmonics components. The non-uniformity measurements are used in one embodiment to adjust current to the shim coils **61** and in another embodiment to adjust the reconstruction processor **52** to account for the non-uniformity.

With reference to FIGURE 2, in one embodiment that employs the sensors **64**, **66**, **68**, **70**, each sensor is a magnetic resonance-based sensor that is independent of the magnetic resonance imaging. For example, FIGURE 2 diagrammatically shows a suitable

magnetic resonance-based sensor **80** that includes a radio frequency generator **82** and a transmit coil or antenna **84**. The transmitted radio frequency energy excites magnetic resonance in a sample **86** disposed near the coil or antenna **84**. A receive coil or antenna **88** also disposed near the sample **86** picks up the magnetic resonance of the sample **86**, and the signal is measured by a radio frequency receiver or sensor **90**. Rather than having separate transmit and receive antennas **84, 88**, a common transmit/receive antenna with suitable send/receive switching can be employed. The sample **86** is disposed in the main magnetic field, for example at the position of one of the sensors **64, 66, 68, 70** shown in FIGURE 1. The antennae **84, 88** are typically disposed near the sample **86** to promote radio frequency coupling. However, the radio frequency generator **82** and the radio frequency receiver or sensor **90** can be disposed inside of or outside of the main B_o magnetic field.

In another embodiment, the shimming processor **60** computes shimming current or currents based on measurements of the main B_o magnetic field acquired by considering the individual elements of a phased array of receivers **34** for the magnetic resonance imaging experiment to provide substantially the same information as a set of receivers **64, 66, 68, 70** shown in FIGURE 1. More generally a phased array coil with two or more elements dispersed at different positions within the bore may be used to provide spatial information about the main B_o magnetic field. This may be achieved by measuring signal being generated for the magnetic resonance imaging experiment, or by introducing additional measurements into the magnetic resonance imaging experiment for the purpose of determining the spatial distribution of the main B_o magnetic field.

In one embodiment, the sample **86** is a fluorine, deuterium, or other sample having a resonance frequency substantially different from that of the ^1H resonance typically imaged in magnetic resonance imaging. In this embodiment, the radio frequency sensor **80** is substantially insensitive to radio frequency excitations produced by the magnetic resonance imaging scanner **10**. In another embodiment, the radio frequency generator **82** and transmit coil or antenna **84** are omitted, and the sample **86** is excited by the radio frequency transmitter **44** and the coil **32** or coils array **34** of the scanner **10** at the imaging ^1H magnetic resonance frequency. Such a passive magnetic field sensor arrangement is used, for example, as a frequency lock coil in some scanners. In this embodiment, a plurality of such passive magnetic field sensors or frequency lock coils

corresponding to the sensors **64, 66, 68, 70** provides information on spatial non-uniformities of the main B_o magnetic field.

In yet another embodiment, the sensors **64, 66, 68, 70** are Hall effect sensors. For example, in FIGURE 3, a Hall sensor **100** includes at least one semiconductor film **102** of indium arsenide, gallium arsenide, indium antimonide, or another semiconductor material exhibiting high Hall voltages, formed on a suitable substantially electrically insulating substrate **104**. The semiconductor film or stack of films **102** is arranged generally transverse to the main B_o magnetic field of the scanner **10**. An electric current (I) passing through the semiconductor film **102** generates a Hall voltage (V_H) transverse to the direction of electric current flow and transverse to the main B_o magnetic field. The polarity and magnitude of the Hall voltage corresponds to the polarity and magnitude, respectively, of the main B_o magnetic field. The Hall effect sensor **100** is substantially insensitive to magnetic resonance excitations produced by the magnetic resonance imaging scanner **10**.

With reference to FIGURE 4, the main B_o magnetic field can also be measured by the scanner **10** itself by using an appropriate pulse sequence. In an illustrated example pulse sequence **120**, a small-angle radio frequency pulse **122** is applied to produce magnetic resonance. The small-angle radio frequency pulse **122** preferably has a flip angle of less than about 5°, and more preferably has a flip angle of between 1° and 5°. In some embodiments the flip angle of the small-angle radio frequency pulse **122** is less than 1°. The small-angle radio frequency pulse **122** is applied without an accompanying magnetic field gradient pulse to excite the imaging volume. A multi-echo gradient readout is performed along the slice-select direction using a multi-lobed magnetic field gradient **126**. In one embodiment, the multi-lobed magnetic field gradient **126** includes five lobes: L1, L2, L3, L4, L5, having a relative lobe area ratio of –a:+b:-b:+b:-a where a and b represent gradient lobe areas and the positive and negative signs represent gradient lobe polarities or directions. In the embodiment illustrated in FIGURE 4, the ratio a:b is 1:2. The gradient reversals produce signal refocusing, and gradient echoes are collected during sampling intervals **130, 132** corresponding to lobes L2 and L4. The gradient echoes are reconstructed into projections along the slice-select direction by applying a Fourier transform reconstruction. A complex phase difference of the projections corresponds to the

main B_o field nonuniformity distribution along the slice-select direction. For a uniform main B_o magnetic field along the slice-select direction, the phase difference is zero.

Multi-echo gradient readouts can be repeated along selected directions to provide three-dimensional data for mapping the main B_o magnetic field. For example, FIGURE 4 shows a second multi-lobed magnetic field gradient **136** along a selected direction transverse to the slice-select direction and at an angle between the phase-encode (y) and readout (x) directions. The multi-lobed magnetic field gradient **136** is produced by a combination of multi-lobed magnetic field gradient components **140, 142** produced by the phase-encode (y) and readout (x) magnetic field gradient coils, respectively. Gradient echoes are read during intervals **144, 146,** and are processed by Fourier transforming and complex phase difference computation. Additional multi-echo gradient readouts can be performed along other directions until the magnetic resonance excited by the small-angle radio frequency pulse **122** decays back to equilibrium. Optionally, additional small-angle radio frequency pulses are applied between successive multi-echo gradient readouts to maintain the magnetic resonance.

In yet another approach for measuring spatial data corresponding to the main B_o magnetic field, the coils of the coils array **34** are used to provide spatially distributed information about the main B_o magnetic field. The coils of the coils array **34** are spatially distributed, and thus can provide spatially distributed information about the main B_o magnetic field in a manner similar to that provided by the dedicated magnetic field sensors **64, 66, 68, 70.**

When the magnetic field sensor or sensors are substantially insensitive to ^{1}H magnetic resonances generated by the magnetic resonance imaging scanner **10,** such as is the case for the magnetic field sensors **80, 100** of FIGURES 2 and 3, the main B_o magnetic field can be monitored substantially any time that the magnetic field gradient coils **30** are inoperative. Thus, data on main B_o magnetic field uniformity can be acquired during portions of the imaging pulse sequences in which no magnetic field gradients are imposed by the gradient coils **30.** The use of the self-energized resonance-based magnetic field sensor **80** operating at a resonance frequency substantially different from the ^{1}H resonance processed by the scanner **10** does not perturb the imaged ^{1}H resonances. Similarly, operation of the Hall effect sensor **100** generally does not perturb the imaged ^{1}H resonances.

In contrast, when one or more of the coils **32, 34** of the scanner **10** are used for monitoring the main B_o magnetic field, or when a resonance-based sensor operating at the imaged ^1H resonance frequency is used, overlap between the imaging and the main B_o magnetic field monitoring should be avoided. In such cases, concurrent magnetic resonance imaging and main B_o magnetic field measuring is accomplished by temporally interleaving pulse sequences used for magnetic field measurement with imaging pulse sequences.

With reference to FIGURE 5, one suitable approach for performing concurrent imaging and main B_o magnetic field measurements is described. In one common magnetic resonance imaging methodology, the imaging proceeds by acquiring successive repetitions, frames or dynamics **140, 142, 144** of imaging data. Each repetition, frame or dynamic **140, 142, 144** images a volume of interest. For example, each frame or dynamic **140, 142, 144** may include acquisition of a plurality of imaging slices **156** spanning the volume of interest. Each frame or dynamic **140, 142, 144** typically spans about around 2-3 seconds, although longer or shorter times are possible. Frames or dynamics **140, 142, 144** are generally separated by dead time intervals of a few tens or hundreds of milliseconds.

During each dead time interval, a main B_o magnetic field measurement **150, 152, 154** is undertaken. For example, each main B_o magnetic field measurement **150, 152, 154** can include the pulse sequence **120** shown in FIGURE 4. The main B_o magnetic field measurements **150, 152, 154** are each short and can be performed within a dead time interval of a few tens or hundreds of milliseconds. The pulse sequence **120** shown in FIGURE 4 can be performed in such a short time interval. In contrast, other typical B_o field mapping sequences, such as FASTERMAP, take longer to perform. A pre-scan FASTERMAP sequence typically takes a timeframe **158** of about five seconds, and thus is unsuitable for measuring the main B_o magnetic field concurrently with magnetic resonance imaging.

Considering for example the main B_o magnetic field measurement **150**, the acquired spatial data pertaining to the main B_o magnetic field is processed by the shimming processor **60** during a calculation time interval **160**, which optionally overlaps the succeeding frame or dynamic **142**. The shimming processor **60** computes one or more shimming currents suitable for compensating for main B_o magnetic field nonuniformities

determined from the data measured during the main B_o magnetic field measurement **150**. The computed shim current or shim currents are applied by the main B_o magnetic field shim controller **62** to correct the main B_o magnetic field during a subsequent frame or dynamic, such during the frame or dynamic **144**. If the combined the main B_o magnetic field measurement **150** and calculation time interval **160** are short enough, then the shimming current or currents may be applied during the next frame or dynamic **142**.

With reference to FIGURE 6, a diagrammatic representation of the shimming processor **60** is described. A spherical harmonics calculator **170** receives suitable measured main B_o magnetic field data and computes spherical harmonic components **172** of the main B_o magnetic field. The spherical harmonics **172** are input to a shim current(s) calculator **176** that computes one or more shim currents **178** for applying to the active shims **61** to compensate for the main B_o magnetic field nonuniformities. In one embodiment, the shim coils **61** are each designed to produce one or a few spherical harmonic shimming components, so that suitable corrective shim currents **178** are readily computed from the spherical harmonics **172** of the main B_o magnetic field.

The magnetic field data received by the spherical harmonics calculator **170** depend upon how the main B_o magnetic field is measured. If dedicated magnetic field sensors such as the sensors **64**, **66**, **68**, **70** are employed, then the magnetic field sensors readout **72** preferably automatically converts the readings into spherical harmonics components. That is, the combination of the magnetic field sensors **64**, **66**, **68**, **70** and the readout **72** preferably act as a magnetic field camera. In this case, the spherical harmonics calculator **170** is suitably omitted. Alternatively, the magnetic field measurements are input to the spherical harmonics calculator **170** in a native format, such as in Cartesian (x,y,z) coordinates or cylindrical (ρ,θ,z) coordinates, and the spherical harmonics calculator **170** performs a coordinates transformation to convert the measured sensors data into spherical harmonic components.

If a magnetic resonance sequence such as the sequence **120** shown in FIGURE 4 is used to measure the main B_o magnetic field data, then the Fourier-transformed gradient readouts $\gamma(L2)$ and $\gamma(L4)$ acquired during the gradient lobes L2, L4 respectively, are processed by a phase difference processor **182** to produce the complex phase difference projection $\Delta\gamma(\mathbf{d})$ where $\mathbf{d}$ represents the projection direction. The spherical harmonics calculator **170** computes spherical harmonics by phase-unwrapping

the complex phase difference projection $\Delta\gamma(\mathbf{d})$ and fitting the unwrapped complex phase difference projection $\Delta\gamma(\mathbf{d})$ to a Legendre polynomial corresponding to a spherical harmonic component.

If data on the spatial distribution of the main B_o magnetic field is acquired using a plurality of coils, such as by using the coils array **34**, then data **184** for each coil including a resonance frequency (ω) and a resonance signal intensity (S) are acquired. A frequency shift calculator **186** computes the frequency distribution by fitting the (S, ω) measurements, corrected for coil sensitivity factors **188**, to a suitable magnetic field model, such as a first-order spatial magnetic field distribution model, or by otherwise analyzing the coils data **184** to obtain the magnetic resonance frequency nonuniformity $\Delta\omega(\mathbf{r})$ as a function of position $\mathbf{r}$ where $\mathbf{r}$ is in Cartesian (x,y,z) coordinates, cylindrical (ρ,θ,z) coordinates, or in another suitable coordinates system. The spherical harmonics calculator **170** converts the magnetic resonance frequency nonuniformity $\Delta\omega(\mathbf{r})$ to a magnetic field nonuniformity $\Delta B_o(\mathbf{r})$ according to ω=gB, where g is the gyrometric ratio and g≅42.58 MHz/T for ^{1}H resonance. The spherical harmonics calculator **170** transforms the magnetic field nonuniformity $\Delta B_o(\mathbf{r})$ into spherical harmonics coordinates. Alternatively, the fitting of the (S, ω) measurements to obtain the magnetic resonance frequency nonuniformity $\Delta\omega(\mathbf{r})$ can be directly performed in spherical harmonics coordinates.

In the illustrated embodiments, the main B_o magnetic field measurements are used to compute corrective shim currents for shimming the main B_o magnetic field during the course of a magnetic resonance imaging session. In another contemplated embodiment, the main B_o magnetic field nonuniformity measurements are used to perform a post-data acquisition correction of the acquired magnetic resonance imaging data that corrects for artifacts in the reconstructed images caused by main B_o magnetic field nonuniformity.

The invention has been described with reference to the preferred embodiments. Obviously, modifications and alterations will occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.